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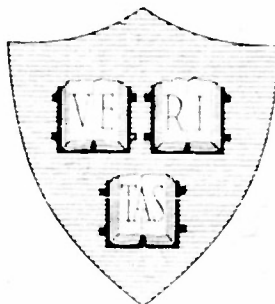
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TANDEM SLIT DIFFRACTION MEASUREMENTS



By

L. R. Alldredge

May 18, 1953

Technical Report No. 176

Cruft Laboratory
Harvard University
Cambridge, Massachusetts

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Contract N5ori-76

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Technical Report

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Tandem-Slit Diffraction Measurements

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Tandem-Slit Diffraction Measurements

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Cruft Laboratory, Harvard University

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Abstract

The diffraction of a plane electromagnetic wave by two identical slits in tandem has been investigated experimentally for normal incidence with the polarization parallel to the edges of the slits.

The slits are assumed to be infinitely long, which condition is approximated experimentally by use of a parallel plate system described earlier by R. V. Row. Measurements have been made for tandem separations of the slits from 0 to nearly 2 wavelengths and for slit widths from 0 to 1.4 wavelengths.

For a tandem-slit separation of zero, which corresponds to a single slit, the results for the transmission coefficient are in good agreement with the theoretical results of P. M. Morse and P. J. Rubenstein. The results show interesting resonance phenomena as the tandem slit-separation is changed.

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I.

Introduction

Microwave techniques have permitted the experimental examination of many scattering and diffraction problems during the past several years. The effect of finite thickness in the diffracting edge of the Sommerfeld problem, which introduces uncertainties when optical frequencies are used, has been studied in detail using these techniques.¹ Many measurements of the scattering from objects and apertures having dimensions comparable to a wavelength have now been made which were not possible with optical techniques.

Most of the microwave diffraction problems that have been worked out have been concerned with diffracting objects of simple shapes confined to a plane with no interaction between objects. As these immediate problems

have been solved, experimenters have turned to more complicated diffracting structures such as two cylinders closely spaced so that interaction is important,² and pairs of parallel wire grids.³ The transmission of a plane electromagnetic wave through two identical tandem slits falls in this category and is the subject of this report. Only the case where the incident wave is polarized parallel to the slit edges is discussed.

The parameters of the investigation are the slit width (same for both slits) and tandem separation. Resonance phenomena which occur in the transmission characteristics as these parameters are varied might be of possible value in the design of components. This problem may prove to be very difficult to analyze mathematically, but, at least, one check on the experimental procedure is available for the case of zero tandem separation (single slit problem⁴).

II.

Experimental Apparatus

General Description

A parallel-plate region utilizing two image planes has been shown to be very useful in the investigation of two dimensional diffraction problems such as the one being studied in this paper. The parallel-plate system built by R. V. Row¹ was available in Cruft Laboratory for use on this problem. Since the detailed description of the system is available in the above reference only a very brief account of it will be given here. Modifications which were necessary for this particular problem will be described in greater detail.

A general view of the equipment is shown in Fig. 1 with the parallel plates open. With the plates closed a region is formed which is bounded on the top and bottom by plates of aluminum 4 feet by 8 feet. These plates are separated vertically by a distance less than one-half wavelength so that only the TEM mode can propagate if all source currents are in the vertical direction.

Calculations for a vertical spacing of 0.50 inch indicate that the next higher mode is attenuated by a factor of about 120 in a distance of one wavelength for an excitation wavelength of 3.182 cm.

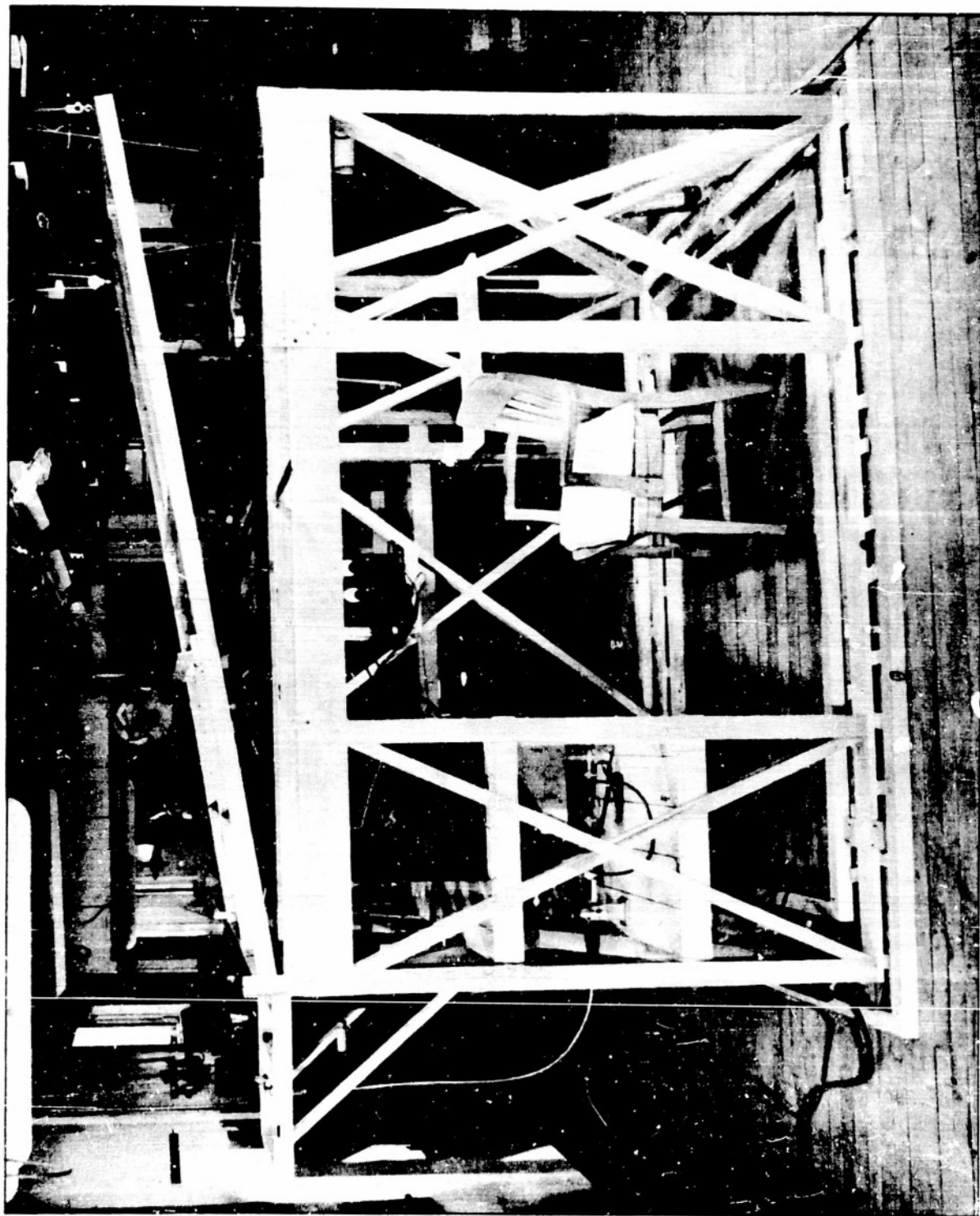


FIG 1 GENERAL VIEW OF EQUIPMENT WITH PARALLEL PLATES OPEN

The vertical spacing is maintained constant by means of 0.50 inch thick wooden wedges around the edge. These wedges are 0.50 x 0.50 inch at the base. The points of the wedges extend 5 inches into the parallel-plate region. The wedges are coated with a heavy layer of colloidal carbon (Aquadag), and serve to reduce reflections of a wave approaching the boundary so that the residual voltage-standing-wave ratio is less than 1.05.

The parallel-plate region should ideally be excited by an extended source at one end which would produce a plane wave in the plane of the diffracting object. A suitable way to do this has not yet been found, and it has been necessary to excite the system by an open-ended waveguide. This gives, in effect, a line excitation and a corresponding cylindrical wave so that corrections must be made in the resulting data on the diffracting objects and the measurements must be restricted to a small region in which a plane wave approximation is accurate.

The desired fields are measured by using a small vertical probe (antenna) which is insulated from and extends up through the bottom plate. The signal from this probe excites a waveguide and this signal can then be used in various standard ways for the determination of phase and amplitude of the original signal.

If the probe is to be used as a traveling probe, a means must be provided so that no discontinuities are left in the lower plate when the probe is moved about.

It should be clear from the above description that the over-all result of the parallel-plate system is to reduce a problem that is essentially infinite in the vertical direction and identical in every horizontal plane and infinite in each horizontal plane to one completely contained within the volume between the parallel plates. This is accomplished by multiple reflections which occur in the two conducting plates. For example: A thin vertical conducting sheet reaching from one side of the system to the other and connecting the top plate to the bottom will appear as an infinite plane; a narrow vertical slit which runs all the way from the top plate to the bottom plate in this thin conducting sheet will appear as an infinite vertical slit in an infinite plane.

Tandem Slits

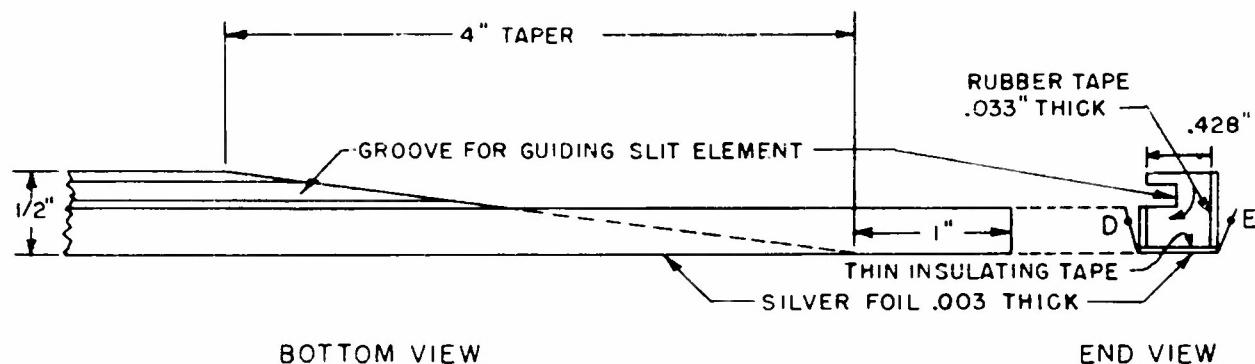
The construction of tandem slits to be used in the parallel-plate region presented several difficult problems; the diffracting edges forming the slits should be very thin compared to a wavelength, should make good contact with the top and bottom plates, and should be quickly and accurately adjustable in tandem separation and slit width. The requirements appear to be mutually exclusive, and it is true that compromises must be made in all of them. The final solution left the leading edge of the slits very thin but used a thicker construction back from the edges to facilitate the mechanical adjustment of slit width and tandem separation.

Figure 2 shows the constriction of the edges forming the slits and how they are adjusted when assembled. The true leading edges which form the slit itself are made of 0.003 inch thick silver foil. A tapered section of heavier stock starts 1 inch back from the leading edge of the slit, and is insulated from the foil.

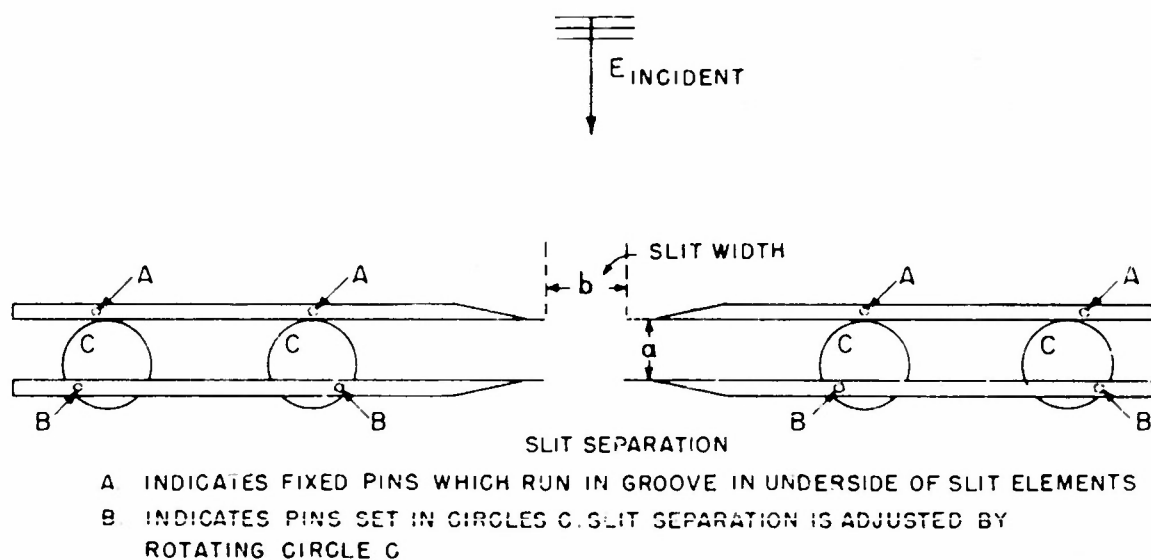
Measurements were made to determine how close the tapered section could be brought to the edge of the diffracting edge. This was done by comparing the diffraction pattern of the thin edge by itself with that obtained with the tapered section in the vicinity of the edge. Large effects were noted when the tapered section was very close to the edge but the effects were negligible when the tapered section was placed 1 inch back from the edge as indicated in Fig. 2(a). The foil was insulated from the larger piece merely to avoid a variable contact. It was felt that no contact at all could be made more sure than to hope for good contact all the way along.

The heavier piece of tapered stock has a thin rubber strip glued to both the top and bottom areas. The silver foil is wider than the required 0.50 inch, leaving sections which are bent over toward the rubber-covered piece of tapered stock. These sections form the lips indicated by D and E in Fig. 2(a). When the parallel plates are closed, the lips bear against the plates all the way out to the diffracting edges. The rubber covering on the heavier piece of tapered stock gives some flexibility and permits the top and bottom to conform to small irregularities in the plates, thereby improving the contact.

The underside of the heavier piece of tapered stock contains a groove which fits over two pins in the bottom parallel plate so as to maintain the



(a) CONSTRUCTION OF EDGES FORMING SLITS



(b) TOP VIEW OF SLIT SYSTEM ASSEMBLED (SCHEMATIC)

FIGURE 2

tandem separation constant when the slit width is varied. The four pins marked "A" in Fig. 2(b) are rigidly fixed in the bottom parallel plate so the distance of the leading slit is maintained at a fixed distance from the source of energy. The four pins marked "B" in Fig. 2(b) are attached to circular plates which rotate in the bottom parallel plate. By adjusting the rotation angles of these four circular plates, the tandem separation, a , can be controlled. The far ends of the slit system are tied together in such a way that the slit widths of the two slits are always equal. A mechanism underneath the parallel-plate system, which reaches out and up to the far ends of the slit system, permits accurate control of and quick adjustment of the slit width by the operator.

Figure 3 is a photograph of one of the diffracting edges used to form the slits. Figure 4 shows the tandem slits in position on the bottom plate of the parallel-plate system. In this photograph, the top plate is in the open position. In this position major adjustments can be made in the diffracting region. In Fig. 5 the same space is shown as in the previous photograph except now the diffracting edges which form the slits are removed and the positioning posts are visible. In this photograph the circular plates carrying positioning posts "B" and the circular plates carrying probe no. 2, described later, have been loosened so as to be seen more easily.

Probe Traverse Mechanisms

A straight dipole antenna (diameter 0.013 inch) is used to explore the vertical electric field E . The probe antenna goes through a very small insulating bushing in the lower parallel plate and protrudes into the parallel-plate region. The probe is an extension of the inner conductor of a coaxial line¹ which, in turn, feeds into a standard (1 x 1/2 inch) X-band guide. The depth of penetration of the probe into the parallel-plate region is continuously variable from zero to approximately 0.3 inch. The whole probe assembly may be tuned for maximum receiving sensitivity by means of a movable shorting plunger on the coaxial line and a movable short circuit in the several standard ways to measure the amplitude and the phase with respect to a reference signal.

Two probes as described above are used. The first one, which was available when this problem was started,¹ is attached to a narrow sliding panel

which forms a part of the lower parallel plate. This narrow plate extends completely across the lower plate and beyond. The probe is made to move along a line across the narrow dimension of the parallel-plate region by operating a rack and pinion traverse mechanism. This probe can be seen in Fig. 4, where it is marked "probe no. 1." The line of motion is parallel to the diffracting objects forming the slits and is 25 cm from the slit nearest the source. If close-in "near field" measurements are desired, the slits are moved closer to probe no. 1. To do this, makeshift slits are used without benefit of the positioning posts.

Probe no. 2, also seen in Fig. 4, is mounted near the edge of a small circular plate (radius 3.5 inches) which is, in turn, mounted off center in a larger circular plate (radius 7.0 inches). The probe can be put any place in a circle 12 inches in diameter by proper adjustment of the rotational position of these two circular plates. Figure 6 is an exploded view of this circular probe traverse mechanism. The waveguide to which the probe antenna is coupled is also visible. Each circular plate has an overlapping rim the underside of which is calibrated in degrees to facilitate adjustment. The center of probe assembly no. 2 is 101.3 cm from the slit nearest the source. This distance was made as great as possible, without getting too close to the absorbing wedges, so as to make far-field measurements possible.

In studying the transmission characteristics of slits a great deal can be learned from only the amplitude and phase of the far field in the direction of incidence. Nevertheless, it seemed wise to have available probes which could be moved so that the symmetry could be checked to insure proper operation of the entire system, and so that field patterns could also be obtained.

Excitation of Parallel-Plate Region

The diffraction problem under consideration requires a plane wave incident upon the leading slit. So far no successful method of exactly meeting this requirement has been devised. The best approximation is usually obtained by moving the source as far away as possible. In this case, where the entire experiment is confined to a small region, it is not possible to get the source very far away from the diffracting slits. Probe no. 2 must be in the far-field region so that the slit positions cannot be moved farther away from the source.

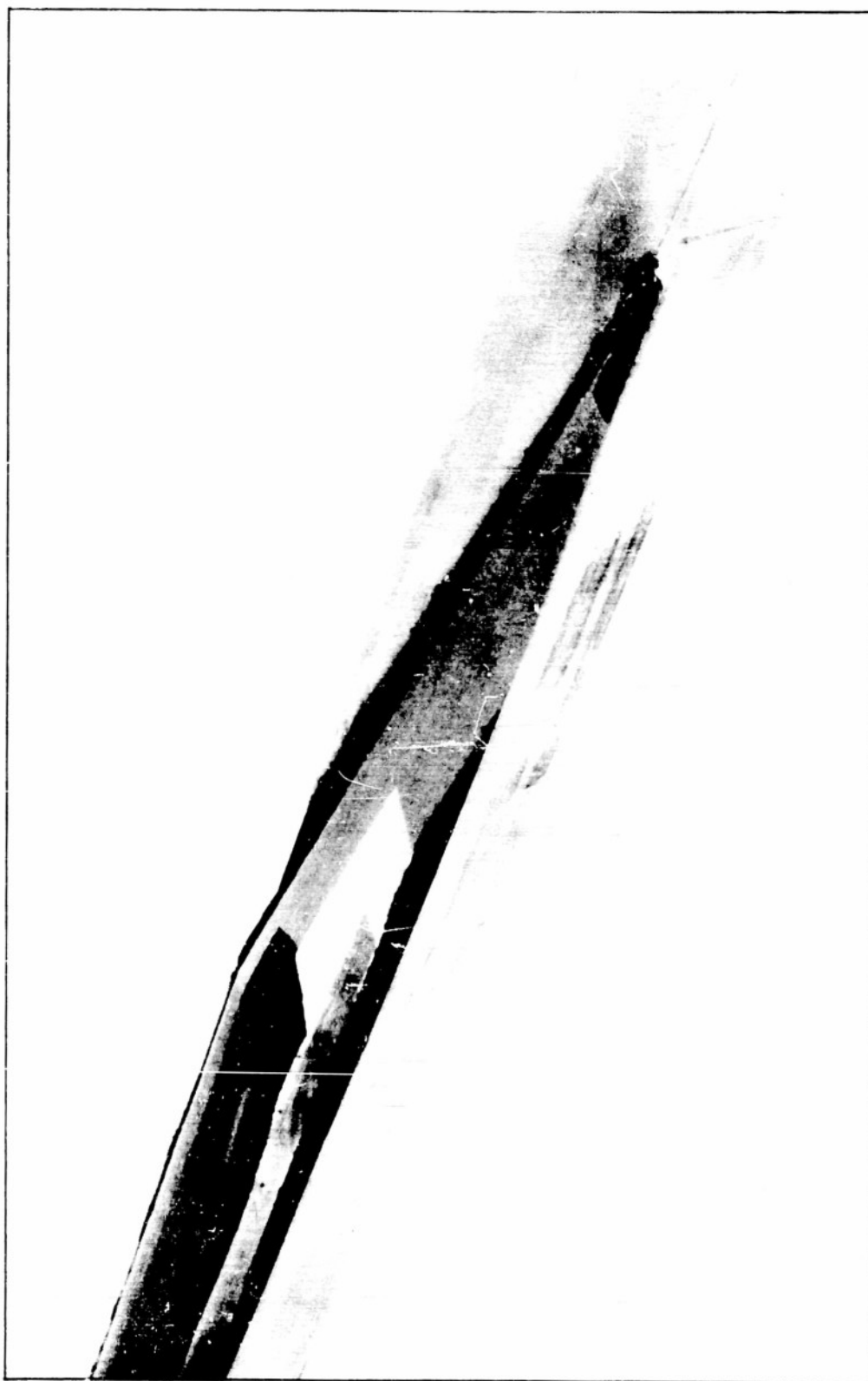


FIG. 3 ONE OF DIFFRACTING EDGES USED TO FORM SLITS

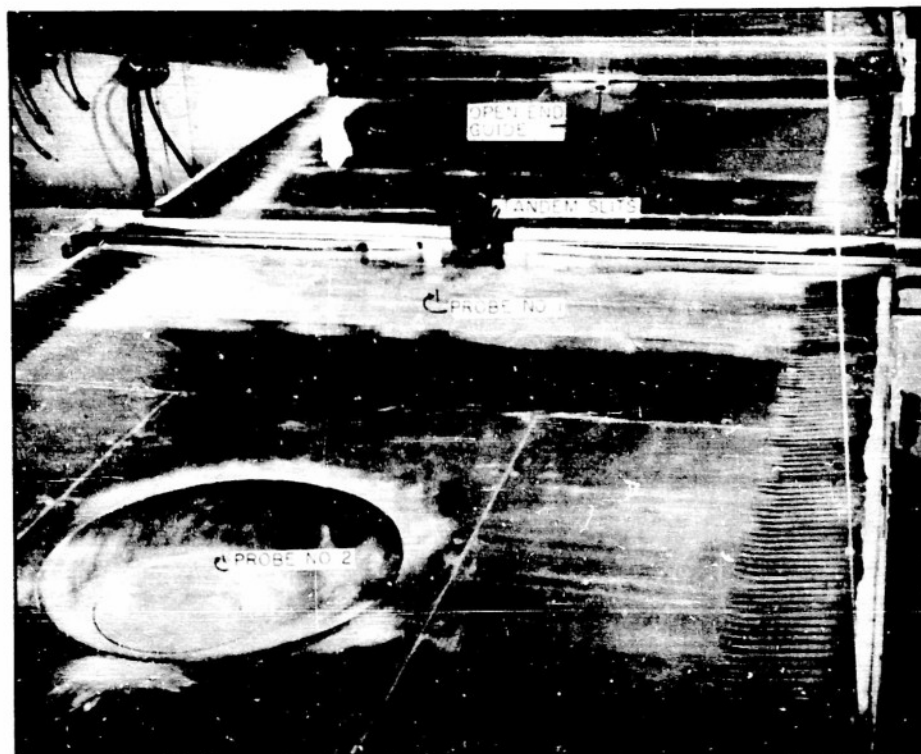
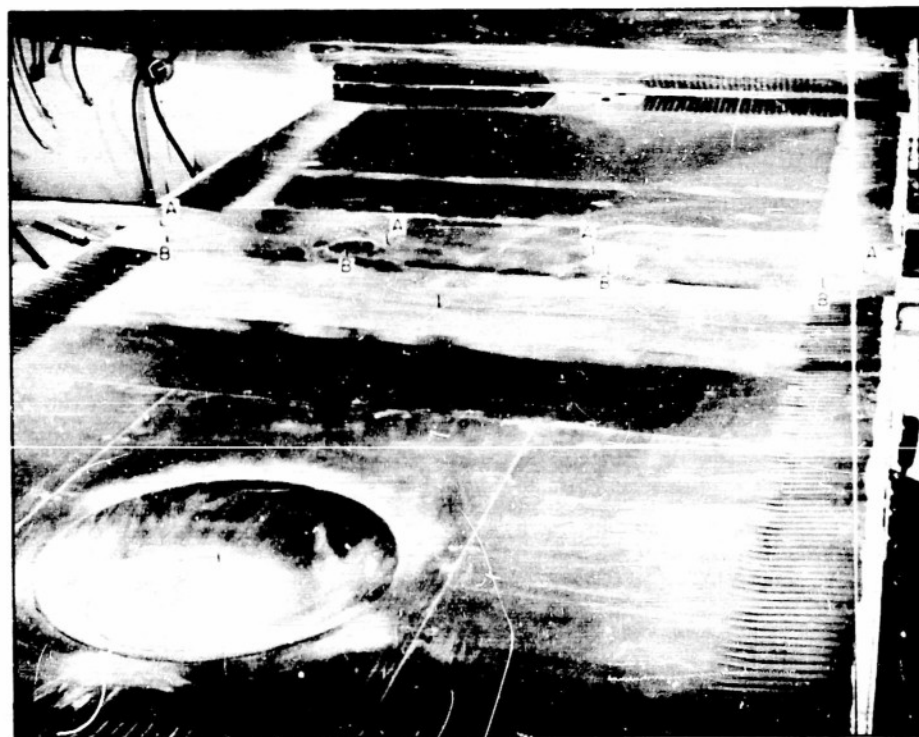


FIG 4 TANDEM SLITS IN PARALLEL-PLATE REGION WITH PLATES IN OPEN POSITION



A-STATIONARY GUIDE POSTS
B-GUIDE POSTS MOUNTED ON CIRCULAR POSITIONING PLATES
FIG 5 PARALLEL PLATE REGION WITH SLITS REMOVED
SHOWING GUIDE POSTS

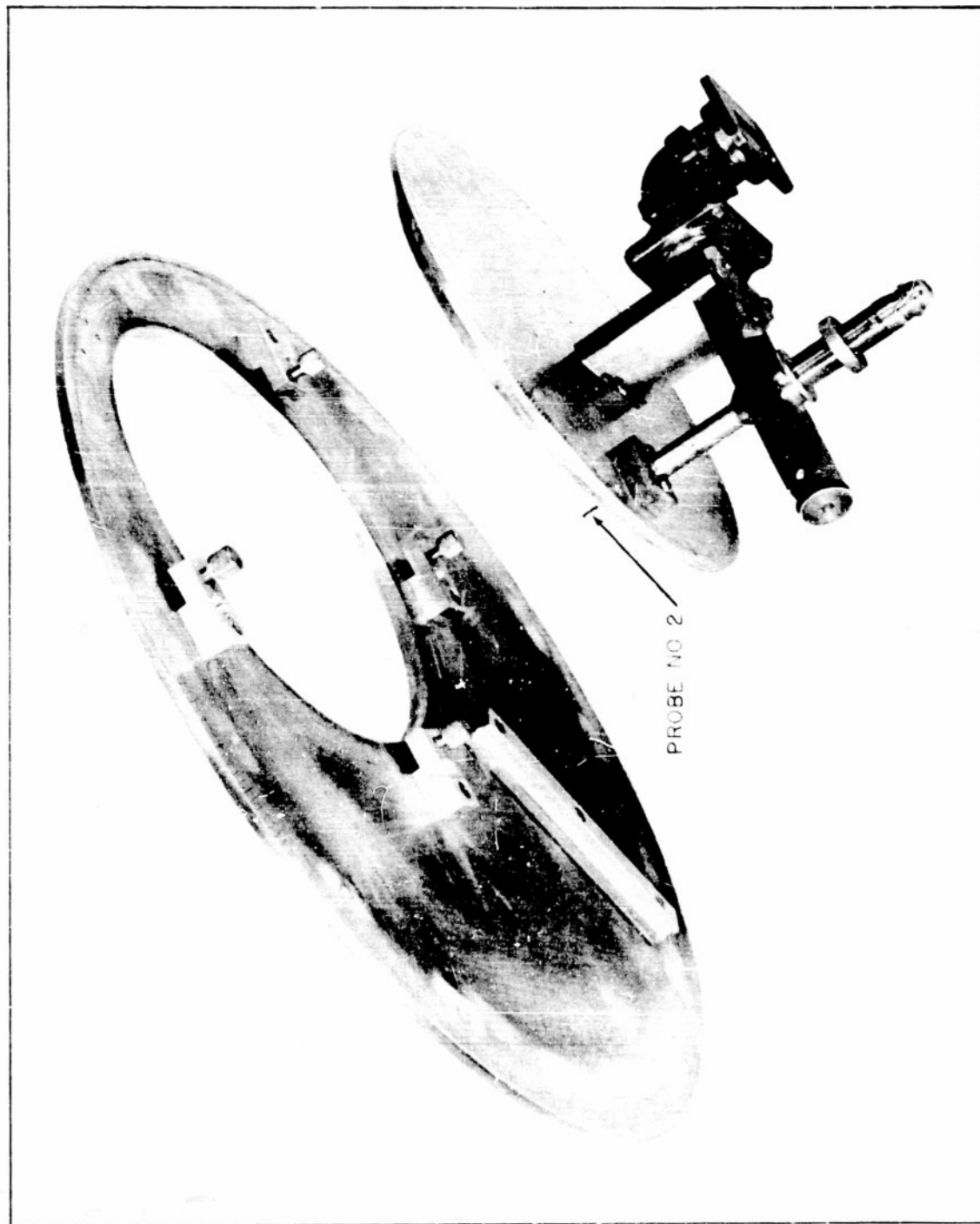


FIG. 6 EXPLODED VIEW OF PROBE TRAVERSE MECHANISM

The source used in this work consists of an open unflanged waveguide placed in the center at one end of the parallel-plate system. The open guide can be seen in Fig. 4 and is indicated in Fig. 7. This source is equivalent to a vertical-line source a short distance inside the mouth of the guide. By measuring the change in phase of the signal picked up on probe no. 1 as it was moved across the region, it was found that the apparent source is 131 cm back from the line of motion of the probe. This means that the apparent line source is 6 cm inside the mouth of the guide and is 106 cm in front of the leading slit when the slits are used in their usual position on the positioning posts.

When the single-edge diffracting pattern for plane-wave incidence is being studied, corrections can easily be made to the experimental results if, in fact, a cylindrical wave is used in place of the desired plane wave. The correction is easy to apply because the scattered field will be the same for plane-wave and cylindrical-wave incidence so long as both have the same amplitude at the diffracting edge. Since the total field measured is the sum of the scattered and incident waves, it is only necessary to determine how the actual incident cylindrical wave differs from the desired incident plane wave at the point of observation and to make the corresponding correction to the data. It would be very helpful if such a simple method could be applied to the tandem slit problem. Such a correction seems hopeless, however, because of the interaction of the slit edges and the fact that the edges of the second slit will no longer fall on the shadow boundary of the edges of the first slit when an incident cylindrical wave is used. For the above reasons, it seems necessary to limit the slit width to a small value so that the incident wave will be a good representation of a plane wave over the slit itself. Many measurements were made for slit widths out to 10 cm (3.14λ), but only data for slit widths less than 1.5λ were used to obtain transmission coefficients, except for some phase information for widths out to 2λ as described later. The apparent line source, as mentioned earlier, is 106 cm in front of the leading slit, which means that for a slit width of 1.5λ the amplitude will not vary more than 0.014 per cent across the slit and the phase will not vary more than 3.4 degrees.

There is a compelling reason for using an open guide as the source rather than a horn or other distributed source. In the course of a set of measure-

ments the slit width is varied so that the reflecting surfaces, and hence the amount of radiation reflected back toward the source, are also varied. If the source presents a large reflecting cross section, this energy will be reflected again and become a part of the effective incident wave. These multiple reflections, which vary as the slit width is changed, are undesirable for they cause effects which cannot be separated from the phenomena under investigation, unless a more complicated monitoring system is adopted. That this effect is not important when the open guide is used is shown by the good agreement which is obtained between the experimental results and theory for the single slit. The reflected energy which is accepted back into the waveguide mouth is large enough to cause serious reactions on the klystron oscillator unless the oscillator is well padded or adjusted to a particularly stable operating point.

Monitoring and Measuring Equipment

Figure 7 shows a schematic layout of the X-band source, and the monitoring and measuring equipment. An X-21 two-cavity klystron is used as the source of approximately 5 watts of microwave power at a free-space wavelength of 3.182 cm. One half of this energy is immediately thrown away by use of a T-junction with a matched load in one arm. This is done to pad the oscillator. The useful signal on the other arm of the T-junction is modulated at 1000 cps by a Luhrs-type 5 faratron ferrite microwave switch which is driven by a Hewlett-Packard oscillator model 205 AG. The waveguide is rotated by 90 degrees on the side of the switch away from the klystron. The plane of polarization of the transmitted signal has been rotated 90 degrees by the switch. Two directional couplers follow. One feeds energy into a terminated slotted section from which a phase-reference signal can be selected and the other provides a signal so that the power level can be monitored as indicated. In actual use the section of guide from the matched load at the bottom to the open-end waveguide is all mounted horizontally directly behind the open guide and is made as short as possible. The X-21 klystron is stable enough that no frequency monitor is needed. When properly adjusted the monitored amplitude level shows only a one or two per cent variation when the slit width is varied from 0 to 10 cm, indicating that the reaction back of the klystron is not serious.

For the purpose of measuring the amplitude of the field the 1000-cps signal from one arm of the phase-measuring tee is fed into the input of a tuned audio-amplifier. The output of this amplifier is connected to a Ballantine vacuum-tube voltmeter. The crystals are square-law detectors.

In making phase measurements, the phase of the signal picked up by the probe is compared with the phase of the known, but adjustable, reference signal selected from the terminated slotted guide. The comparison is made using the magic-tee bridge with balanced loads and crystals and a bolometer amplifier with a VTVM output meter. The location of the probe in the slotted guide is measured to 0.001 inch by an Ames gauge. For each phase determination the position of this reference probe is determined for a minimum indication on the vacuum-tube voltmeter. The details of this phase measuring system are described in a report by T. Morita⁵ and will not be given here. The X-21 klystron exhibited very good frequency stability so that the requirement of having the same electrical length in the two paths used for phase comparison, did not seem to be important.

Discussion of Results

Diffraction Patterns

It was decided that the emphasis of this study would be placed on the determination of the amplitude (in the far field directly behind the slits) and the transmission coefficient. This decision was made because it appeared unlikely that a suitable analytic description could be constructed for the general diffraction pattern. Before this decision was made, however, several field-pattern measurements were taken and are included in this report.

The first-pattern measurements were taken before the slit system described earlier was completed and before the high-power X-21 klystron was available. A slit system made of silver foil bent around a rectangle of polyfoam was used. It was built in two separate halves so that although the tandem separation was fixed ($7/8\lambda$ in this case), the slit width could be varied by pulling the two halves apart. A 2K 25 klystron operating at a free-space wavelength of 3.185 cm was used as a source of energy. The slit system was placed with its trailing edge 12.8 cm in front of the probe no. 1. The output of the vacuum-tube voltmeter was recorded as probe no. 1 was

moved parallel to the slit system. The results are shown in Fig. 8. Measurements were made for slit widths of 2λ , 3λ , 4λ , 5λ and 6λ . There was difficulty in precisely aligning the two halves of the slit system which accounts for the slight lack of symmetry in the two sides of the curves. It was, in fact, this difficulty which led to the construction of the slit system described earlier using positioning guide posts.

The curves in Fig. 8 show how complicated the near field patterns may become. It should be borne in mind that these curves are no longer very good approximations to the plane-wave incidence case, for with such large slit widths the effect of the line source at such a close distance is probably quite appreciable. The difference is, however, probably one of degree rather than kind. In this case as well as in all cases to follow where the slit separation is greater than 0.5 wavelength, absorbing wedges were placed between the planes forming the slits back near the edge of the parallel-plate region. These absorbers prohibit energy, being propagated between the planes forming the slits, from being reflected from the edge of the parallel-plate region and hence back into the slit area.

A few additional pattern measurements were taken after the accurate slit system was completed, as a check on their precision. A slit tandem separation of 5.95 cm (largest available with this slit system) was chosen, and the leading edge of the slit system was 25 cm in front of probe no. 1. Probe no. 2 was kept 76.3 cm behind the line of motion of probe no. 1. Both probes were moved parallel to the conducting planes forming the slits yielding the curves shown in Fig. 9 for various values of slit width. In this case the square root of the VTVM readings are given so that the ordinate is proportional to the field strength. The results from the two probes have not been normalized with respect to each other, but all curves for a given probe are normalized with respect to one another. Here again, these curves are not good approximations of what a plane incident wave would yield because of the large slit widths used. The important thing is that a high degree of symmetry is obtained, giving assurance that the slit system is satisfactory. Probe no. 1 was perhaps a little too far away to measure a true near field.

It is of interest to note how the pattern broadens out as the slit width is narrowed down. This is expected if the slit is thought of as the radiating source for the region beyond the slit system.

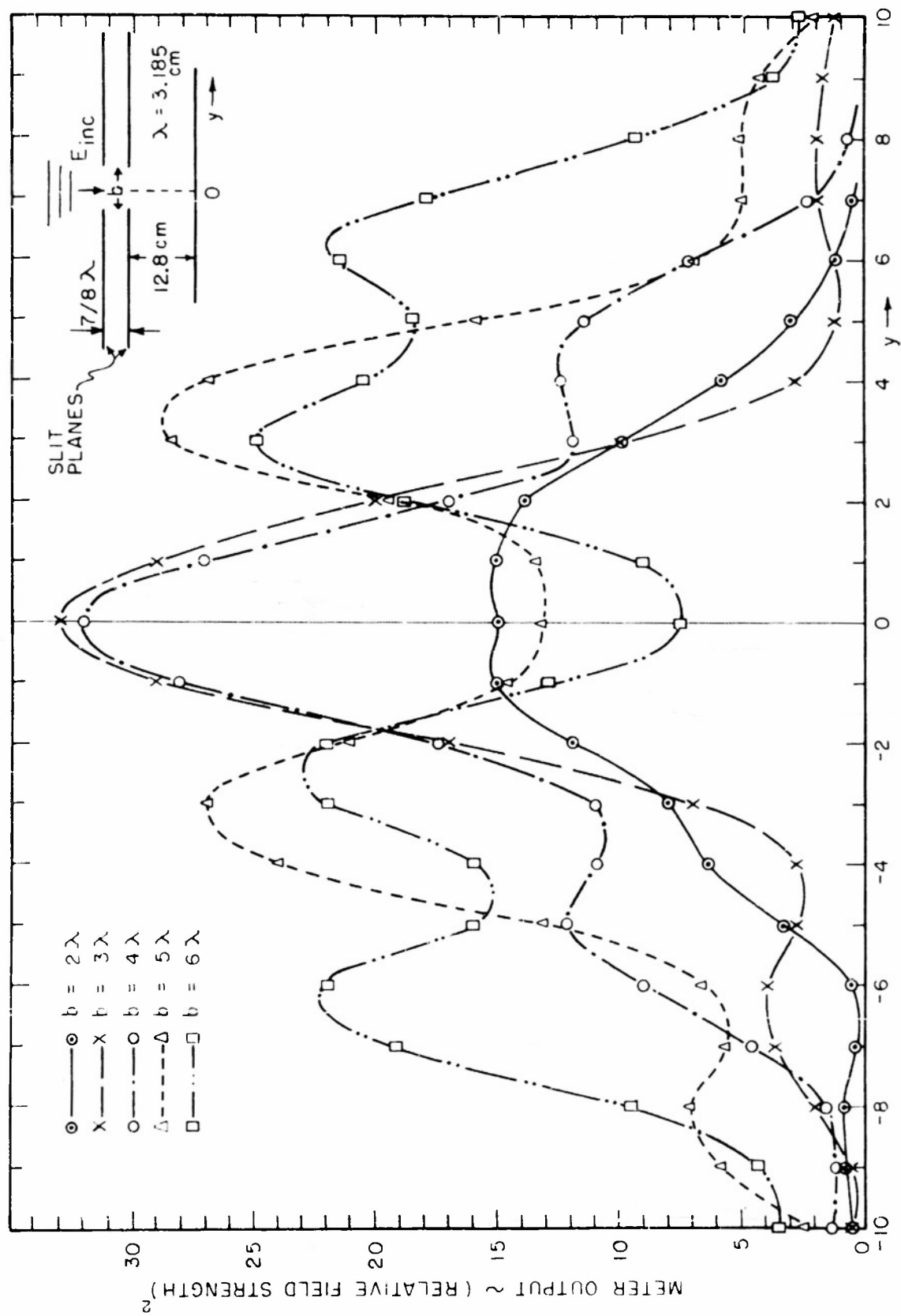


FIG. 8 TANDEM SLIT DIFFRACTION PATTERN IN NEAR FIELD

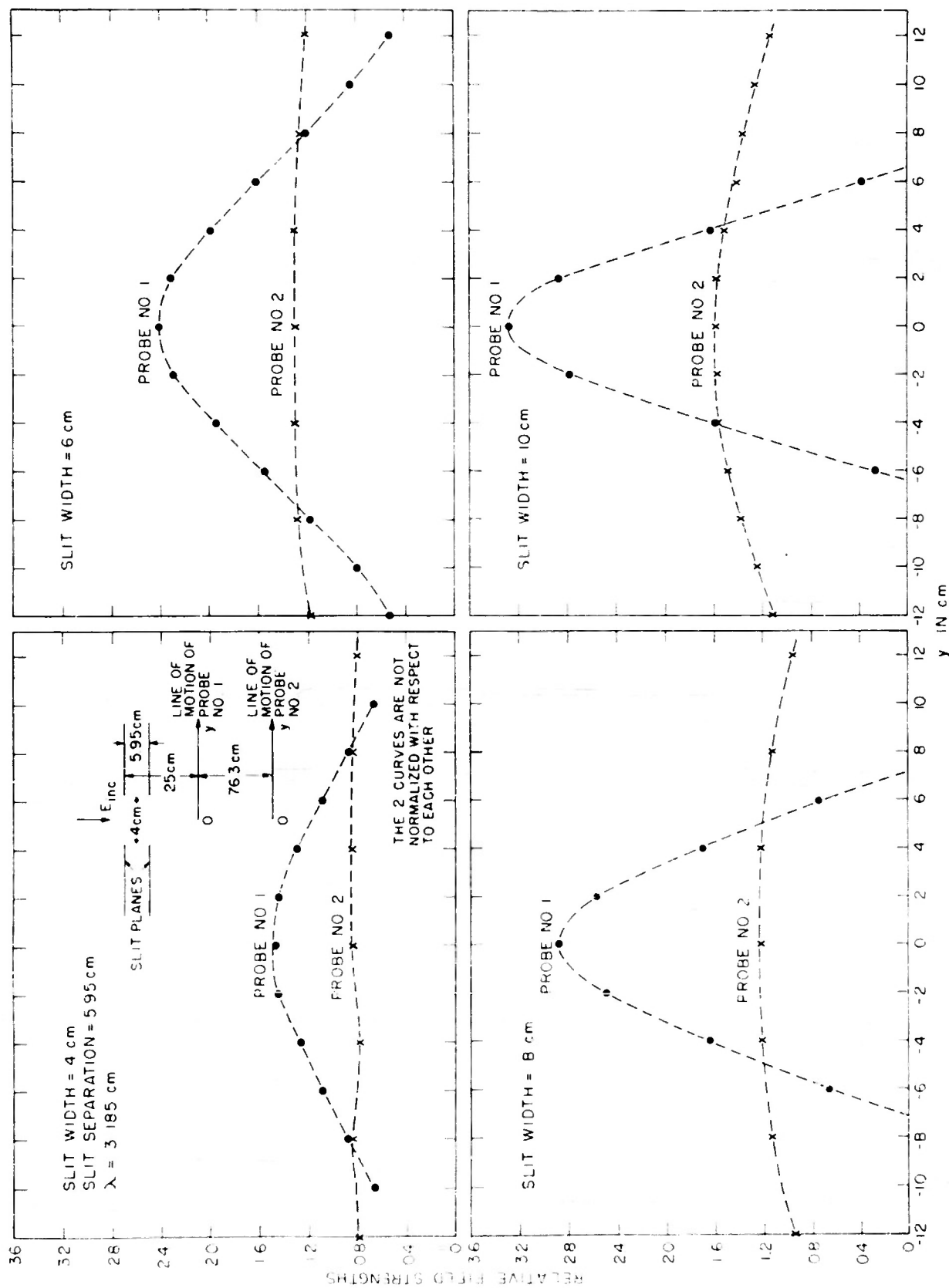


FIG. 9 AMPLITUDE PATTERNS IN NEAR AND FAR FIELDS FOR TANDEM SLITS

Transmission Coefficient

The transmission cross section for an aperture is the ratio of the total power transmitted through the aperture to the power per unit area incident on the aperture.

For a plane wave incident on an aperture in a single conducting plane, the transmission cross section is proportional to the imaginary part of the radiation-field amplitude in the direction of incidence.⁶ The transmission coefficient for the aperture is the transmission cross section divided by the area of the aperture. The same type of analysis applied to the geometry of a single slit shows similar results; in this case, however, the problem is two-dimensional and the cross section should be divided by the slit width, b , rather than by the area. When the second slit is put behind the first slit, the analysis becomes much more complicated. A preliminary analysis indicates that it is the total power scattered outside of the region, between the conductors forming the slits, which is proportional to the imaginary part of the far field amplitude rather than the transmitted power. However, by analogy to the single-slit problem, the term "transmission coefficient" is used in this report to mean the imaginary part of the far-field amplitude divided by the slit width.

The phase measurements are made with respect to an arbitrary reference zero point. When the slits are wide open, the transmission coefficient must equal 1, and the amplitude considered as imaginary for the purpose of computing the transmission coefficient. There is still some difficulty in experimentally establishing this reference zero point for the phase measurements, because the incident wave will no longer be a good approximation of a plane wave if the slits are opened very wide. Moreover, when the slits are open wide the detecting probe will no longer be far enough in back of the slit to measure the true radiation field. Most of this uncertainty can be dispelled by observing both the way in which the phase changes as the slit, for zero tandem separation (single slit), is widened, and how the resulting transmission coefficients, computed by assuming various zero phase reference points, compare with the theoretical values.⁴

Experimentally, it was found that as the slit width was increased, the phase smoothly and monotonically increased until a peak was reached at a slit

width of approximately 1λ . As the slit width was further increased, the phase dropped until at a width of approximately 1.25λ , a broad minimum was noted with the phase 3.9 degrees below the first peak. After this, the phase slowly increased until at a width of 2λ , a second peak, 3.7 degrees above the first peak, was recorded. The experimental data were plotted in three different ways by assuming in turn that the far-field amplitude was purely imaginary at one of the extremes listed above. It was found that each of these three choices, for determining the zero reference phase angle, resulted in experimental curves that were in reasonable agreement with the theoretical curve, but the best fit occurred when the far-field amplitude was taken as imaginary for the most extreme slit width used (2λ).

There is still some uncertainty in the phase angle, and it is fortunate that this factor is not very critical. The behavior of the trigonometric functions is such that a slight error in the zero of the phase angle will have an important effect only at small slit widths where, for other reasons, the data were not reliable. Experimentally it was found that reproducible phase measurements could not be made for slit widths less than 0.4λ , because the amplitude of the field was too small.

The small phase-resonance effect described above for the single slit was also found to occur for tandem separations up to 2 cm. For greater tandem separations the phase monotonically changed and seemed to reach a constant value at the maximum slit width used. In all cases the far-field amplitude was taken as imaginary at the greatest slit width used.

The above procedure for choosing the zero phase angle is justified by the agreement with the theoretical wave for a single slit. When the experimental and theoretical curves for the single slit are compared for large slit widths, however, discrepancies begin to appear for slit widths greater than 1.3λ . These discrepancies are not of the type that can be corrected by changing the zero-phase angle-reference-point, without causing major discrepancies for small slit widths. For this reason it seems proper to conclude that at these large slit widths, the undesirable effects of a cylindrical incident wave and of probe no. 2 being too close to the slits are becoming important in determining the amplitude of the signal. Because of this, the final results do not show data for slit widths greater than 1.4λ .

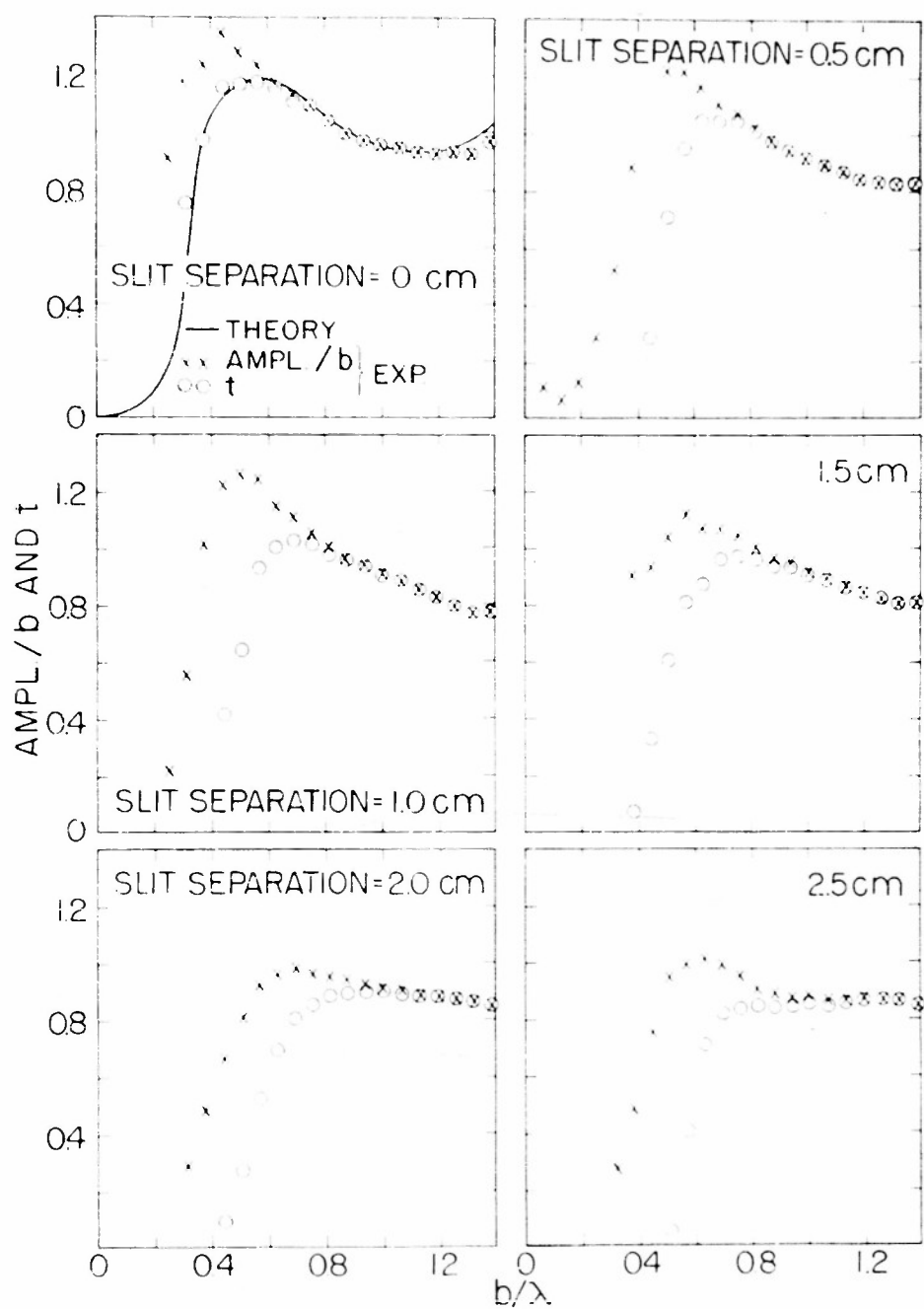
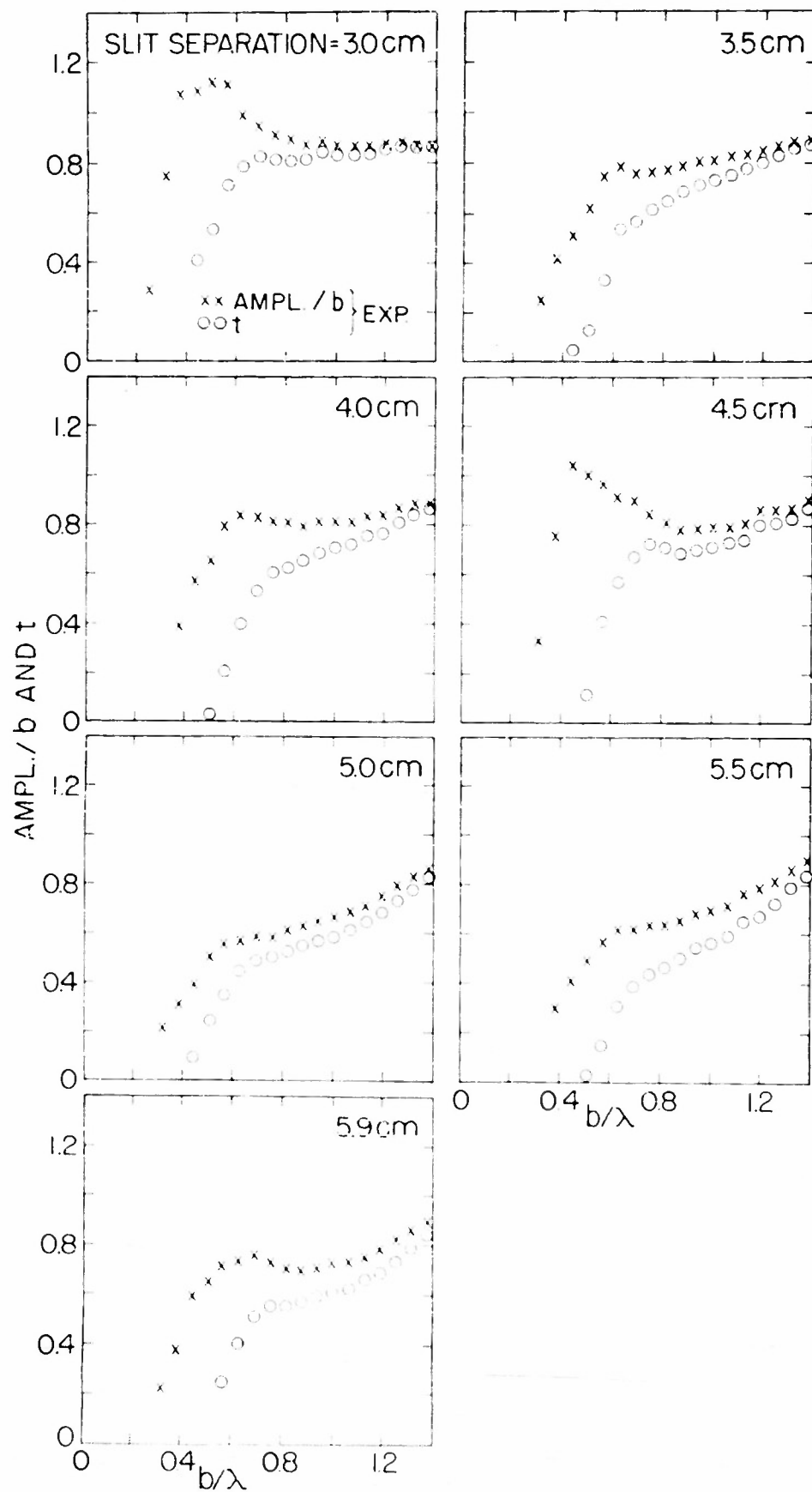


FIG. 10 TRANSMISSION COEFFICIENT t AND
NORMALIZED AMPLITUDE IN FAR ZONE
FOR TANDEM SLIT DIFFRACTION



The following procedure was used in obtaining the remainder of the data. First, the desired tandem separation was set by adjusting the circular plates carrying the rear slit-positioning posts. An entire amplitude curve was then taken as a function of slit width. For each value of slit width the monitored level was recorded to permit normalization. Between successive values of slit width the top plate of the parallel-plate region was raised just enough to remove the pressure from the slit edges so the slit width could be changed. All of these operations were done from a single operating position. Measurements were repeatable to an accuracy of about 3 per cent. After the amplitude measurements were complete, the phase-reference line was connected and the range of slit widths was covered again to obtain the phase measurements. In making the phase measurements, much more care was needed than with the amplitude measurements. The amplitude of the reference-line signal was changed often to keep it nearly at the same level as the signal derived from probe no. 2. This procedure was repeated for each tandem separation. Later, curves were taken by varying the tandem separation while holding the slit constant. These latter curves provided a method of normalizing the original curves to each other. Three such independent checks proved to be very consistent.

The final results are displayed in Fig. 10, where both the amplitude divided by slit width and the transmission coefficients are plotted as functions of the slit width for a variety of tandem slit separations.

The experimental results for the transmission coefficient for zero tandem separation (single slit) are seen to agree quite well with the Morse-Rubenstein⁴ computed values. As the tandem separation increases, the primary peak in the transmission coefficient decreases and moves toward larger slit widths. The curve changes quite markedly when the tandem separation goes from 1.5 cm to 2.0 cm. This change may be associated with the fact that at 2.0-cm separation the space between the planes forming the slits can now act as a waveguide for the H_{10} mode. Similar changes seem to occur at each new tandem separation that can permit the next higher mode to propagate between the conductors forming the slits. This change in behavior, which seems to be associated with the modes that can be propagated between the conductors, appears in greater relief in the amplitude data. Large peaks in the amplitude have developed for tandem

separations of 1.5 cm, 3.0 cm, and 4.5 cm. These peaks are greatly reduced when the slit separations increase respectively to 2.0 cm, 3.5 cm, and 5.0 cm. It would be interesting to investigate this effect in detail to determine how sharp the transition is. It might be caused by a large amount of energy being coupled into the waveguide formed by the slit assembly or it may be that the incident wave sees a greatly modified input impedance at the leading slit.

Acknowledgment

An attempt to formulate this problem analytically is being undertaken. It is hoped that this will lead to answers to some of the questions raised above.

The author acknowledges the valuable help given by R. V. Row and R. D. Kodis as this work progressed.

Additional Reports Issued by Cruft Laboratory

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| 2 | D. D. King, "Measured Impedance of Cylindrical Dipoles," 1946. <u>J. Appl. Phys.</u> , Oct. 1946. |
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